

# Vehicle Acceleration Modeling in PC-Crash

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## Abstract

PC-Crash™, a widely used crash analysis software package, incorporates the capability for modeling non-constant vehicle acceleration, where the acceleration rate varies with speed, weight, engine power, the degree of throttle application, and the roadway slope. The research reported here offers a validation of this capability, demonstrating that PC-Crash can be used to realistically model the build-up of a vehicle's speed under maximal acceleration. In the research reported here, PC-Crash 9.0 was used to model the full-throttle acceleration capabilities of three vehicles with automatic transmissions – a 2006 Ford Crown Victoria Police Interceptor (CVPI), a 2000 Cadillac DeVille DTS, and a 2003 Ford F150. For each vehicle, geometric dimensions, inertial properties, and engine/drivetrain parameters were obtained from a combination of manufacturer specifications, calculations, inspections of exemplar vehicles and full-scale vehicle testing. In each case, the full-throttle acceleration of the vehicles modeled in PC-Crash showed good agreement with the acceleration of the real vehicles in our road tests.

## Introduction

According to Gillespie [1], the following equation will yield a theoretical upper limit on the longitudinal acceleration rate,  $a_x$  (g), for low to moderate speeds:

$$a_x = 550 \cdot \frac{1}{V} \cdot \frac{HP}{W} \quad (1)$$

In this equation,  $V$  is the forward speed of the vehicle (ft/sec),  $HP$  is the engine horsepower, and  $W$  is the weight of the vehicle (lb). This equation neglects resistance forces acting on the vehicle, and so, it does not yield realistic acceleration values. Nonetheless, it does illustrate two important principles. First, the maximum rate at which a vehicle can accelerate decreases as its speed increases [2]. Second, the acceleration rate depends on the engine power to weight ratio.

At times, these aspects of vehicle acceleration can become important within an accident reconstruction context. For example, knowing a vehicle's acceleration limits can enable a reconstructionist to determine the maximum speed of a vehicle that is involved in a collision after starting from a stop at a known location. A vehicle's acceleration limits might also be significant when trying to determine whether or not a driver stopped their vehicle at a stop sign. And finally, a vehicle's

acceleration limits may become important to know when analyzing vehicle motion during events, such as police pursuits, that might involve limit acceleration.

PC-Crash incorporates the capability for modeling non-constant vehicle acceleration, where the acceleration rate varies with speed, weight, engine power, the degree of throttle application, and the roadway slope. In the research reported here, this capability in PC-Crash 9.0 was used to model the full-throttle acceleration capabilities of three vehicles with automatic transmissions – a 2006 Ford Crown Victoria Police Interceptor (CVPI), a 2000 Cadillac DeVille DTS, and a 2003 Ford F150.

To model non-constant, speed-dependent acceleration, the PC-Crash engine and drivetrain model uses the following inputs: (1) maximum engine power; (2) maximum engine and drag-limited vehicle speeds; (3) drivetrain efficiency; (4) drive mode (front, rear, or four-wheel drive); (5) number of gears; (6) differential and transmission gear ratios; (7) the variation of engine torque with engine speed; and (8) gear shift engine speeds with the associated time delay. Typically, manufacturer specifications or road test data report the maximum engine power, the maximum engine speed (redline), the drive mode, the number of gears and the differential and transmission gear ratios. Sometimes they also report the maximum drag-limited vehicle speed, which is used within PC-Crash as a part of the calculation of air resistance. Within PC-Crash, these values are entered by selecting "Engine/Drivetrain" from the "Vehicle" drop-down menu.

Several options exist for obtaining and specifying the variation of engine torque with engine speed for any particular vehicle make and model. One option is to use one of the four stock curves available in PC-Crash (normal, sport, diesel, turbo diesel). Another option is to obtain a publically available torque curve from an aftermarket equipment manufacturer (K&N Filters, for instance, [www.knfilters.com](http://www.knfilters.com)). Yet another option would be to conduct dynamometer testing with an exemplar vehicle, from which the torque curve can be developed. Such testing could also reveal the gear shift engine speeds and the associated time delay. Otherwise, typical or reasonable values could be entered for these shift parameters or they could be obtained from a full-scale acceleration road test with an exemplar vehicle. Similarly, the drivetrain efficiency could be determined from full-scale vehicle testing or a range of reasonable values could be considered. The PC-Crash Operating Manual [3] states that efficiencies between 70 and 90 percent are normal.

Beyond these parameters, the vehicle's geometric dimensions, inertial properties and tire model parameters can affect the resulting acceleration rate. Some of these parameters are available from manufacturer specifications or they can be calculated based on manufacturer specifications. For instance, a vehicle's moments of inertia can be estimated using formulas in References 4 and 5. Many of these parameters can also be obtained from inspection of an exemplar vehicle. Within PC-Crash, the user can select an appropriate tire size and the software will calculate the tire dimensions. Alternatively, the user can enter a tire diameter and width manually. PC-Crash also offers two tire models – the linear tire model and the TM-Easy tire model. For the modeling reported in this paper, the TM-Easy tire model was used with longitudinal and lateral tire force curves constructed from typical tire parameter reported in Reference 6. Within PC-Crash, geometric dimensions, inertial properties and tire model parameters are entered by selecting "Vehicle settings" or "Tire model" from the "Vehicle" drop-down menu.

Once the vehicle's engine, drivetrain, geometric, inertial and tire parameters are specified, the user can then specify the degree of throttle application through the Sequences dialogue boxes. The shift points and associated time delay are also entered in this area of the software. The sequences are entered into PC-Crash by selecting "Sequences" from the "Dynamics" drop-down menu.

In addition to these factors that PC-Crash takes into account, atmospheric conditions also affect a vehicle's acceleration capabilities [1, 7]. Generally, atmospheric conditions that increase the amount of oxygen available to an engine will increase the power and torque of that engine. So, engine output will increase as air temperatures and humidity levels decrease and as absolute pressures increase. Thus, testing conducted at a particular time and location will likely need to be adjusted before it can be applied to a different time and location to account for any differences in air temperature, absolute pressure and humidity. In this research, a method was also developed and validated to make adjustments for atmospheric conditions.

## Dynamometer Testing

***Ford Crown Victoria Police Interceptor:*** On January 3 and 4, 2012, we inspected and documented the 2006 Ford Crown Victoria Police Interceptor depicted in Figure 1. This vehicle was a rear-wheel drive, four-door sedan with an automatic transmission, an 8-cylinder, 4.6 liter, gasoline engine and a weight of 4,646 pounds. The vehicle was equipped with Goodyear Eagle RS-A tires of size P235/55 R17.

Engine and drivetrain parameters that were obtained for this vehicle from manufacturer specifications are listed in Table 1. Testing of this vehicle was conducted for this study on a dynamometer (dyno) at MAC Autosport in Parker, Colorado to obtain torque and power curves in relation to engine speed (data sampled at a rate of 50 Hz). The photograph of Figure 2 shows this vehicle on the dyno. At the time of this dyno testing, the temperature was approximately 69° F, the pressure was 24.52 inches of mercury (in-Hg), and the humidity was 10%.



Figure 1. Exemplar 2006 Ford CVPI

Table 1. CVPI Engine and Drivetrain Parameters

Maximum SAE Engine Power (@ 5000 RPM)	250 HP
Maximum Engine Speed	5500 rpm
Maximum Engine Torque	297 ft-lb
1 <sup>st</sup> Gear Ratio (x:1)	2.82
2 <sup>nd</sup> Gear Ratio (x:1)	1.5
3 <sup>rd</sup> Gear Ratio (x:1)	1
4 <sup>th</sup> Gear Ratio (x:1)	0.7
Final Drive Ratio (x:1)	3.55



Figure 2. Exemplar 2006 Ford CVPI

The results of this dyno testing for both wheel horsepower and wheel torque are shown in Figure 3. In this graph, engine RPM is shown on the horizontal axis, wheel horsepower on the left vertical axis, and wheel torque on the right vertical axis. When inputting a torque curve into PC-Crash, the torque values should be those obtained at the crank, not at the wheels. To arrive at these values for this vehicle, the torque curve measured at the wheels was scaled such that the maximum torque coincided with the maximum engine torque reported in the manufacturer specifications.

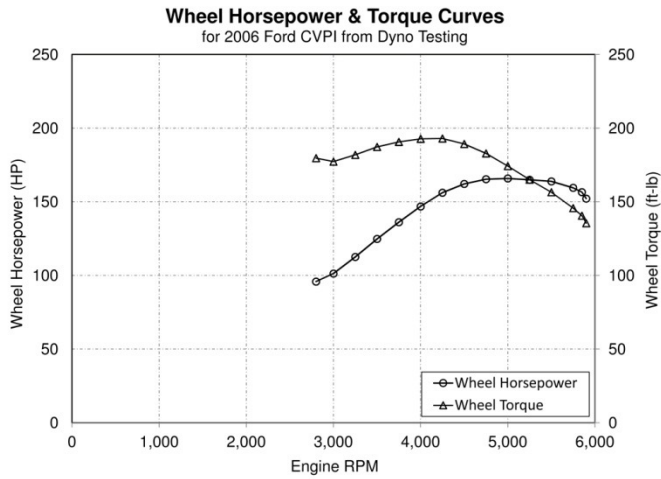


Figure 3. CVPI Dyno Testing Results

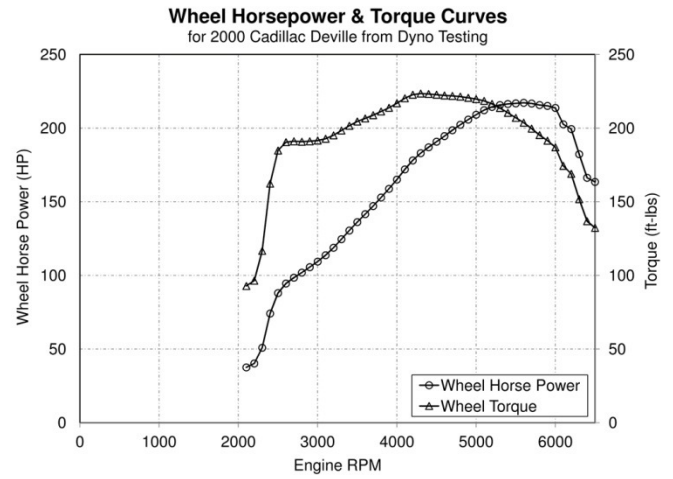


Figure 5. Cadillac Dyno Testing Results

**Cadillac DeVille:** On December 8, 2011, the authors inspected and documented the 2000 Cadillac DeVille DTS depicted in Figure 4. This vehicle was a front-wheel drive, four-door sedan with an automatic transmission, an 8-cylinder, 4.6 liter, gasoline engine and a weight of 4,078 pounds. The vehicle was equipped with Hankook Optimo H418 tires of size P235/55 R17. Engine and drivetrain parameters that were obtained for this vehicle from manufacturer specifications are listed in Table 2. To supplement these specifications, testing of the vehicle was conducted on a dynamometer at Racing Trenz in Denver, Colorado to obtain torque and power curves. This data was sampled at a rate of 200 Hz. At the time of this dyno testing, the temperature was around 58° F, the pressure was 24.70 in-Hg, and the humidity was 13.7%.

The results of this dyno testing are shown in the graph of Figure 5. In this graph, engine RPM is again shown on the horizontal axis, wheel horsepower on the left vertical axis and wheel torque on the right vertical axis. Again, when entering the torque curve into PC-Crash, the torque measured at the wheels was scaled such that the maximum torque coincided with the maximum engine torque reported in the manufacturer specifications.



Figure 4. Exemplar 2000 Cadillac DeVille

Table 2. Cadillac Engine and Drivetrain Parameters

Maximum SAE Engine Power (@ 6000 RPM)	300 HP
Maximum Engine Speed	6700 rpm
Maximum Engine Torque	295 ft-lb
1 <sup>st</sup> Gear Ratio (x:1)	2.96
2 <sup>nd</sup> Gear Ratio (x:1)	1.626
3 <sup>rd</sup> Gear Ratio (x:1)	1
4 <sup>th</sup> Gear Ratio (x:1)	0.68
Final Drive Ratio (x:1)	3.71

**Ford F150:** The Ford F150 used for this research was a model year 2003, XLT, 4x4 (modeled and tested in 2WD), SuperCab with an automatic transmission. This vehicle is depicted in the photograph of Figure 6. For modeling the full-throttle acceleration of this vehicle, publically available wheel horsepower and torque curves were used. Specifically, K&N Engineering ([www.knfilters.com](http://www.knfilters.com)) offered horsepower and torque curves from dyno testing for a 2001 Ford F150, which has essentially identical engine and drivetrain specifications to a 2003 model year. This dyno testing was run at a temperature around 70° F, a pressure of 29.21 in-Hg, and a humidity of approximately 48%.

The results reported by K&N Engineering are graphed in Figure 7. In this graph, engine RPM is again shown on the horizontal axis, wheel horsepower on the left vertical axis and wheel torque on the right vertical axis. Engine and drivetrain parameters that were obtained for a 2001 Ford F150 from manufacturer specifications are listed in Table 3. Again, when entering the torque curve into PC-Crash, the torque measured at the wheels was scaled up such that the maximum torque coincided with the maximum engine torque reported in manufacturer specifications.



Figure 6. Exemplar 2003 Ford F150



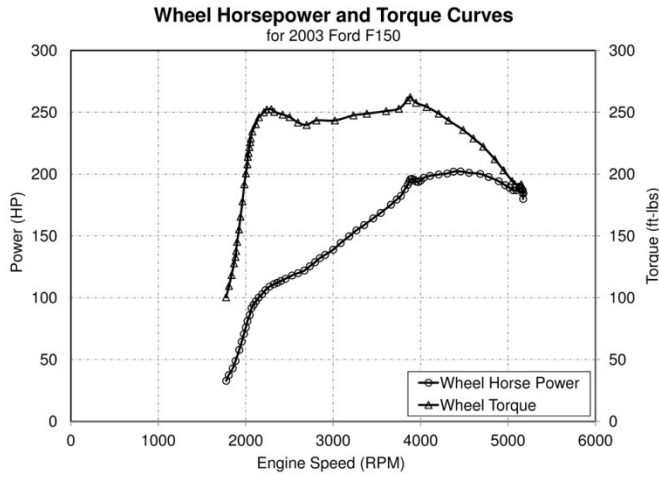


Figure 7. Ford F150 Dyno Testing Results

Table 3. Ford F-150 Engine and Drivetrain Parameters

Maximum SAE Engine Power	260 HP
Maximum Engine Speed	5100 rpm
Maximum Engine Torque	350 ft-lb
1 <sup>st</sup> Gear Ratio (x:1)	2.84
2 <sup>nd</sup> Gear Ratio (x:1)	1.55
3 <sup>rd</sup> Gear Ratio (x:1)	1
4 <sup>th</sup> Gear Ratio (x:1)	0.7
Final Drive Ratio (x:1)	3.55

## Road Tests

In modeling the acceleration capabilities of a vehicle in PC-Crash, one unknown factor will be the drivetrain efficiency. The PC-Crash manual states that a value of 70 to 90% is normal for this input [2]. In our modeling, the efficiency was used as an optimizing parameter in obtaining a match between the speed versus time and speed versus distance curves for full-throttle acceleration obtained in PC-Crash and full-throttle acceleration obtained during a road test of an exemplar vehicle.

**2006 Ford Crown Victoria Police Interceptor:** On January 3, 2012, the authors conducted a road test with the exemplar CVPI shown in Figure 1. This test was conducted on a flat, straight asphalt surface in Aurora, Colorado and consisted of full-throttle acceleration from 0 mph up to a speed just over 70 mph. At the time of the test, the temperature was approximately 55° F, the pressure was 24.53 in-Hg, and the humidity was 22%. During the test, the vehicle was instrumented with a VBOX data acquisition system from Racelogic. The VBOX system utilized three GPS antenna to measure the test vehicle's translational and angular positions and its speed throughout the tests at a frequency of 20 Hz. These sensors were attached magnetically to the roof of the CVPI. This test was also captured with video cameras recording at a rate of 30 frames per second. The results of this test are shown in Figure 8. In this graph, time is shown on the horizontal axis and speed on the vertical axis.

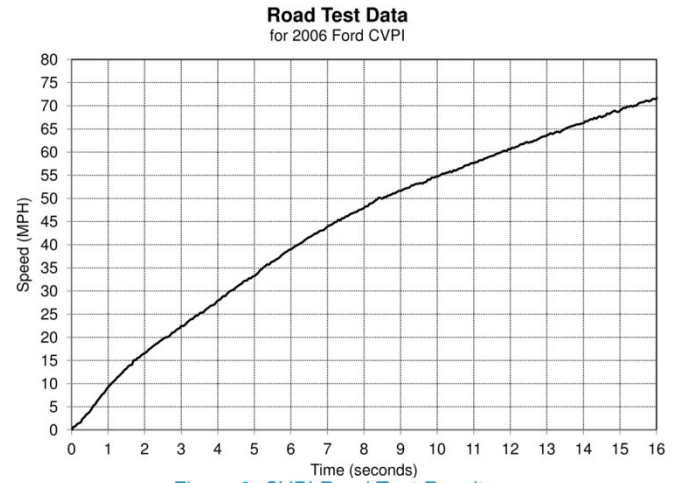


Figure 8. CVPI Road Test Results

**2000 Cadillac DeVille:** On December 8, 2011, the authors conducted a road test with the exemplar Cadillac DeVille shown in Figure 4. This test, which was conducted on a relatively flat section of highway in Denver, Colorado, consisted of full-throttle acceleration from 0 mph up to 75 mph. At the time of the test, the temperature was approximately 20° F, the pressure was 24.63 in-Hg, and the humidity was 81%. This test was documented by videotaping the speedometer of the vehicle at a frequency of 30 Hz. The results of this test are shown in Figure 9. Again, in this graph, time is shown on the horizontal axis and speed on the vertical axis.

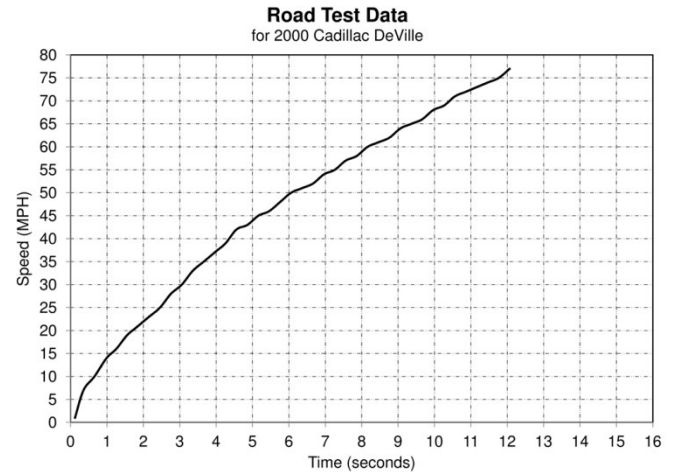


Figure 9. Cadillac DeVille Road Test Results

**2003 Ford F150:** On November 12, 2012, the 2003 Ford F150 XLT SuperCab depicted in Figure 6 was inspected and documented. This vehicle had part-time four-wheel drive (tested in 2WD), an automatic transmission, an 8-cylinder, 5.4 liter, gasoline engine and a weight of 5,002 pounds. The vehicle was equipped with Hankook DynaPro AT RF08 tires of size P265/70 R17. As a part of our documentation of this vehicle, a road test was conducted on a flat, straight asphalt surface in Greenwood Village, Colorado. This testing consisted of two full-throttle acceleration runs from 0 mph up to a speed just below 25 mph. For these runs, the vehicle was instrumented with a VBOX data acquisition system. At the time of the tests, the temperature was approximately 48° F, the pressure was 24.38 in-Hg, and the humidity was 30%. The

results of this testing are shown in the graph of Figure 10, which again has time on the horizontal axis and speed on the vertical axis.

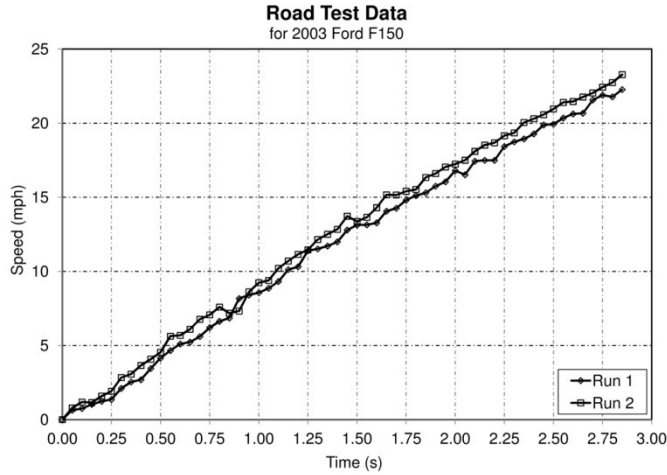


Figure 10. Ford F150 Road Test Results

## Accounting for Atmospheric Conditions

As was previously noted, atmospheric conditions that increase the amount of oxygen available to an engine will increase the power and torque of that engine. So, engine output will increase as air temperatures and humidity levels decrease and as absolute pressures increase. Thus, testing conducted at a particular time and location will likely need to be adjusted before it can be applied to a different time and location to account for any differences in air temperature, absolute pressure and humidity. In the research reported here, such adjustments were accomplished by applying equations from SAE Surface Vehicle Standard J1349 (Engine Power Test Code – Spark Ignition and Compression Ignition – As Installed Net Power Rating) [8].

SAE J1349 describes a method for correcting observed power and torque to reference conditions or to historical conditions at a specific time and location. The methodology in SAEJ1349 allows for calculation of a power correction factor utilizing an assumed engine mechanical efficiency of 85%. This efficiency refers to mechanical losses occurring internal to the engine. The equation for the power correction factor, PCF, is as follows:

$$PCF = \left( \frac{99}{Pa_{do}} \right) \left( \frac{t_o + 273}{298} \right)^{0.5} \quad (2)$$

In this equation,  $Pa_{do}$  is the observed, dry inlet air supply pressure in kPa and  $t_o$  is the inlet air supply temperature in degrees C. The inlet dry air pressure is calculated with the following equation:

$$Pa_{do} = Pa_o - E_s \times RH \quad (3)$$

In this equation,  $Pa_o$  is the absolute ambient air pressure,  $E_s$  is the saturation vapor pressure, and  $RH$  is the relative humidity. A high-accuracy equation for  $E_s$  is as follows.  $T$  is in degrees C and the coefficients 0-9 are as listed in Table 4.

$$E_s = \frac{6.1078}{p^8} \quad (4)$$

$$p = C_0 + T(C_1 + T(C_2 + T(C_3 + T(C_4 + T(C_5 + T(C_6 + T(C_7 + T(C_8 + T(C_9)))))))) \quad (5)$$

Table 4. Coefficients for Equation (5)

$C_0$	0.999997	$C_5$	-2.99E-11
$C_1$	-0.009083	$C_6$	2.19E-13
$C_2$	7.87E-05	$C_7$	-1.79E-15
$C_3$	-6.11E-07	$C_8$	1.11E-17
$C_4$	4.39E-09	$C_9$	-3.1E-20

Relative humidity is calculated with the following equation, where  $T$  is the temperature in degrees C and  $T_d$  is the dew point temperature in degrees C:

$$RH = \left[ \frac{(112 - 0.1 \times T + T_d)}{(112 + 0.9 \times T)} \right]^8 \quad (6)$$

Once the correction factor is calculated, it can be used in the following equation to correct the power:

$$Bp_c = (1.176 \times PCF - 1.176)Bp_o \quad (7)$$

In this equation,  $Bp$  refers to the power at the crank and subscripts c and o denote corrected and observed, respectively. The following equation relates horsepower to torque ( $\tau$  in ft-lbs) and it can be used to correct the torque values once the corrected horsepower has been calculated.

$$\tau_c = \frac{5252 \times Bp_c}{RPM} \quad (8)$$

## Results and Analysis

Figure 11 is a graph that compares the results of simulating full-throttle acceleration for the 2006 Ford CVPI in PC-Crash with the road test data for this vehicle. In this instance, the PC-Crash simulation utilized a drivetrain efficiency of 73% with shifts occurring at 5300 RPM and shift delays of 0.2 seconds. Over the course of the roughly 16 seconds shown on this graph, the road test vehicle traveled around 1027 feet and the simulated vehicle traveled around 999 feet, an error of 28 feet (-2.8%).

Figure 12 is a graph that compares the results of simulating full-throttle acceleration for the 2000 Cadillac DeVille DTS in PC-Crash with the road test data for this vehicle. In this instance, the PC-Crash simulation utilized a drivetrain efficiency of 85% with shifts occurring at 6100 RPM and shift delays of 0.2 seconds. In the road test for this vehicle, the distance traveled was not measured directly, and so, no distance comparison was performed for this vehicle. The simulated vehicle, however, showed good agreement with the road test vehicle in terms of the length of time it took to reach various speeds. The maximum time

error of approximately ½ second occurred early in the acceleration run at a speed of 20 mph.

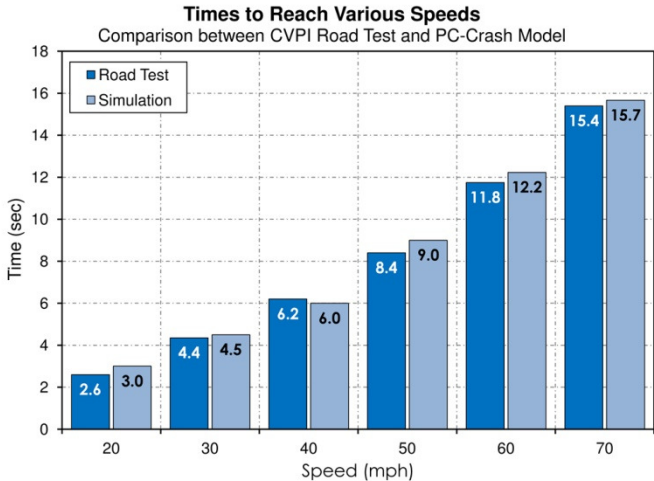


Figure 11. Comparison of Road Test and Simulation (CVPI)

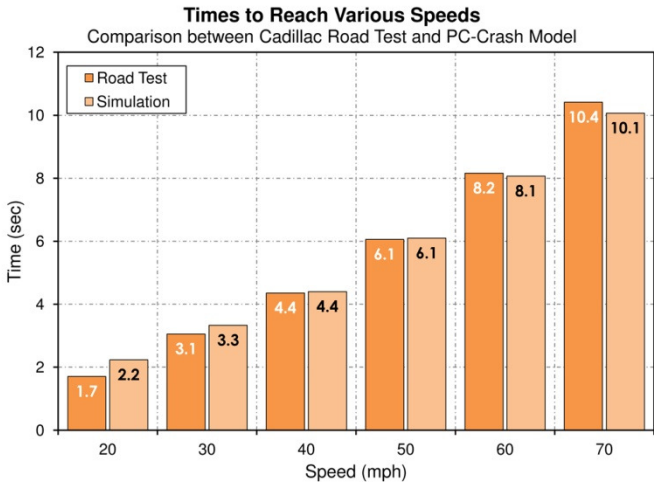


Figure 12. Comparison of Road Test and Simulation (Cadillac DeVille)

Finally, Figure 13 is a graph that compares the results of simulating full-throttle acceleration for the 2003 Ford F150 in PC-Crash with the road test data for this vehicle. In this instance, the PC-Crash simulation utilized a drivetrain efficiency of 78% and no shifts occurred over the short duration of the test. Over the course of the roughly 3 seconds shown on this graph, the road test vehicle traveled around 65 feet and the simulated vehicle traveled around 62 feet, an error of 3 feet (-4.8%). As Figures 11 through 13 demonstrate, in all three cases, the PC-Crash acceleration modeling produced vehicle motion that showed good agreement with the road test data.

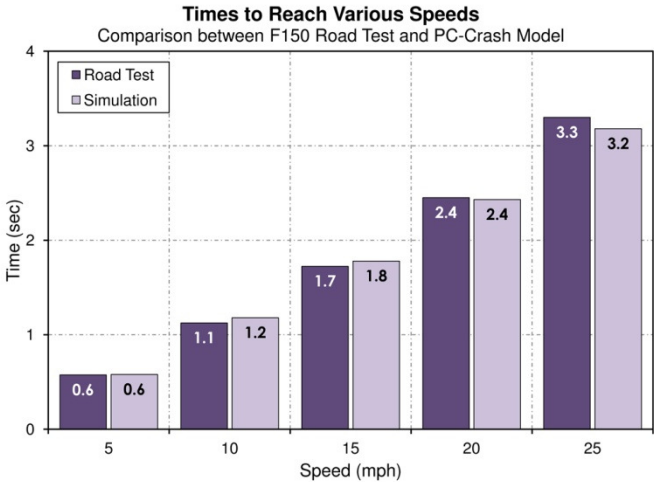


Figure 13. Comparison of Road Test and Simulation (Ford F150)

To validate our procedure for correcting dyno and road test data for atmospheric conditions, data generated by the Michigan State Police (MSP) for a 2006 Ford Crown Victoria Police Interceptor was utilized [9]. This data was generated as a part of testing that the MSP conducts each year of the performance capabilities of each new model year's police vehicles, testing that they have been conducting for more than 25 years. This data included full-throttle acceleration tests in which each vehicle started from a stop and the time and distance for each vehicle to accelerate to various speeds were documented. This testing was conducted at the Chrysler Corporation Chelsea Proving Grounds, around 60 miles west of Detroit, Michigan. To validate our procedure, the power and torque that were documented in Denver, Colorado for the 2006 CVPI were corrected to the atmospheric conditions that were present at the time of the MSP testing. The simulated full-throttle acceleration run for this vehicle was then rerun using the corrected power and torque numbers. Figure 14 compares our simulation to the data from the MSP testing. As this graph shows, the correction for atmospheric conditions resulted in good agreement between the simulation and the road test data from MSP, indicating that the correction procedure works well.

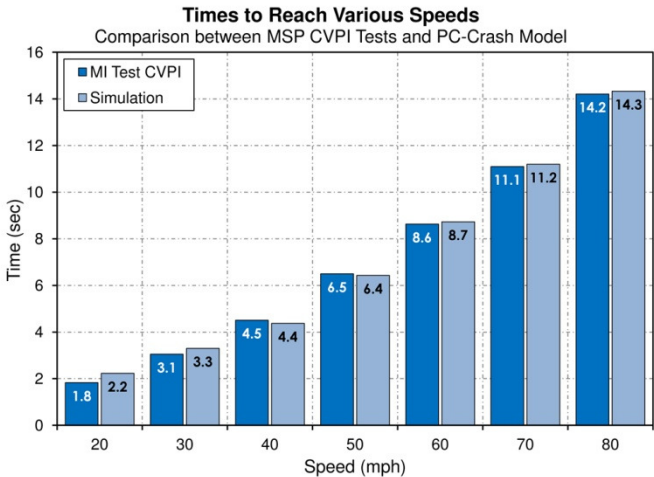


Figure 14. Comparison of Michigan State Police Road Test and Simulation (2006 CVPI)

## Discussion

This study has shown that PC-Crash can be used to model realistic full-throttle acceleration of vehicles with automatic transmissions. This modeling relied on manufacturer specifications and full-scale vehicle testing to obtain the following inputs for PC-Crash: (1) maximum engine power; (2) maximum engine and drag-limited vehicle speeds; (3) efficiency; (4) drive mode (front, rear, or four-wheel drive); (5) number of gears; (6) differential and transmission gear ratios; (7) the variation of engine torque with engine speed; and (8) gear shift engine speeds with the associated time delay. For each vehicle analyzed in this research, the engine and drive-train parameters in PC-Crash were optimized to obtain a match of the velocity versus time and velocity versus distance data with those obtained from the full-scale, full-throttle acceleration tests with exemplar vehicles. This study has also shown that a PC-Crash model can be built based on test data from a particular location and time, and then, that model can be adjusted to model a vehicle's acceleration capabilities at a different time and location.

## Conclusions

1. Vehicle torque and horsepower curves can be used in conjunction with road test data to model real-world vehicle acceleration capabilities in PC-Crash.
2. Vehicle acceleration capabilities modeled at one location under a particular set of atmospheric conditions can be applied at another location with different atmospheric conditions by applying a power correction factor.
3. The full-throttle acceleration of the three vehicles modeled in PC-Crash showed good agreement with the acceleration of the real vehicles in our road tests.

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